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Wind and Current Forces on Canadian Forces Ships During Tug Operations

Kevin McTaggart

Defence R&D Canada

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Abstract

This report presents predictions of wind and current forces on Canadian Forces ships during tug operations. Longitudinal and transverse forces are given as functions of incident flow direction. For the ship geometries considered, transverse forces arising from transverse flows are much greater than longitudinal forces from longitudinal flows. For winds or currents from the bow quarter (45 degrees), transverse forces are much greater than longitudinal forces. The report includes tables of wind and current forces acting on HALIFAX, IROQUOIS and AOR ships. In an operational context, the greatest errors in force predictions will likely be due to errors in wind or current velocities.

Résumé

Dans ce rapport, nous présentons des prédictions sur les forces dues au vent et au courant exercées sur les navires des Forces canadiennes pendant les manouvres de remorquage. Les forces longitudinales et transversales sont données en fonction de la direction de l'écoulement incident. Les forces transversales produites sur les navires étudiés par les écoulements transversaux sont très supérieures aux forces longitudinales dues aux écoulements longitudinaux. Les vents ou les courants des trois-quarts avant (45 degrés) exercent des forces transversales très supérieures aux forces longitudinales. Ce rapport présente les tableaux des forces dues au vent et au courant exercées sur les navires Halifax, Iroquois et AOR. Pendant les opérations, les erreurs les plus élevées dans la prédiction de la force seront probablement celles engendrées par les erreurs sur les vitesses du vent et du courant.

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Executive summary

Introduction

In response to a request from NOTC VENTURE, DRDC Atlantic has developed predictions of wind and current forces on HALIFAX, IROQUOIS, and AOR ships during tug operations. Longitudinal and transverse forces are presented for head, bow quartering, and beam winds and currents.

Principal Results

Air and water drag coefficients for Canadian Forces ships have been estimated using results available in the open literature. Similarly, the variation of longitudinal and transverse drag forces with flow direction is modelled using a formulation presented in the open literature. For the ship geometries considered, transverse forces arising from transverse flows are much greater than longitudinal forces from longitudinal flows. For winds or currents from the bow quarter (45 degrees), transverse forces are much greater than longitudinal forces. Due to the variation of forces with the square of flow velocity, relative errors in estimated flow velocity can lead to relative force errors which are approximately twice as large.

Significance of Results

Tables presented in this report can be used to estimate forces on Canadian Forces ships during tug operations. When using the tables, allowance should be made for uncertainties in flow velocity estimates, which can significantly influence drag forces.

Future Plans

The information in this report will be useful for future modelling and simulation of ship operations.

Kevin McTaggart; 2002; Wind and Current Forces on Canadian Forces Ships During Tug Operations; DRDC Atlantic TM 2002-192; Defence R&D Canada – Atlantic.

Sommaire

Introduction

À la suite d'une demande du CEOM Venture, RDDC Atlantique a calculé des prédictions sur les forces dues au vent et au courant exercées sur les navires Halifax, Iroquois et AOR pendant les manouvres de remorquage. Nous présentons les forces longitudinales et transversales pour des vents et des courants debout, trois-quarts avant et de travers.

Résultats principaux

Nous avons estimé les coefficients de résistance des navires des Forces canadiennes à partir des résultats contenus dans les documents non classifiés. De façon analogue, nous avons utilisé une formule trouvée dans les documents non classifiés pour décrire la variation des forces de résistance longitudinales et transversales avec la direction des courants. Les forces transversales produites sur les navires étudiés par les écoulements transversaux sont très supérieures aux forces longitudinales dues aux écoulements longitudinaux. Les vents ou les courants des trois-quarts avant (45 degrés) exercent des forces transversales très supérieures aux forces longitudinales. Puisque les forces varient avec le carré de la vitesse d'écoulement, les erreurs relatives sur l'estimation de la vitesse d'écoulement engendreront des erreurs relatives environ deux fois plus élevées sur la force.

Importance des résultats

Nous présentons dans ce rapport, des tableaux permettant d'estimer les forces subies par les navires des Forces canadiennes pendant les manouvres de remorquage. L'utilisateur de ces tableaux devra prévoir une marge pour les incertitudes des estimations de la vitesse d'écoulement, laquelle a un impact important sur les forces de résistance.

Plans pour l'avenir

Les données contenues dans ce rapport seront utiles aux travaux futurs de modélisation et de simulation des manoeuvres des navires.

Kevin McTaggart; 2002; Wind and Current Forces on Canadian Forces Ships During Tug Operations; DRDC Atlantic TM 2002-192; Defence R&D Canada – Atlantic.

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1 Introduction

During operations with tugs assisting larger ships, wind and ocean currents can significantly influence required towing and pushing forces. To facilitate safe tug operations, VENTURE, the Naval Officers Training Center (NOTC), requested that the Directorate of Maritime Ship Support (DMSS) develop tables of wind and current forces acting on HALIFAX, IROQUOIS, and AOR ship classes. DMSS subsequently tasked DRDC Atlantic to perform this work, which is documented in this technical memorandum. Section 2 describes methods for predicting wind forces on ships, and is followed by Section 3 giving a similar treatment for current forces on ships. The drift velocity induced by current and wind is discussed in Section 4. Section 5 gives predicted wind and current forces for Canadian Forces (CF) ships, followed by a brief discussion of prediction uncertainties in Section 6. Final conclusions are presented in Section 7.

2 Wind Forces on Ships

Wind forces acting on ships are discussed in many references. McTaggart and Savage [1] describe model tests conducted on a generic frigate model to determine wind forces influencing ship capsize. Van Manen and van Oossanen [2] give an overview of wind forces on ships. Among the various references available, Blendermann [3] is very useful for estimating wind forces on ships for various heading angles. The wind forces acting on a ship can be expressed as:

$$F_x^a = \frac{1}{2}\,\rho_a\,V_a^2\,A_l^a\,C_{Dl}^a\,\frac{\cos\epsilon_a}{1\;-\;\frac{\delta_a}{2}\left(1-\frac{C_{Dl}^a\,A_l^a}{C_{Dt}^a A_t^a}\right)\sin^2 2\epsilon_a} \qquad (1)$$

$$F_y^a = \frac{1}{2}\,\rho_a\,V_a^2\,A_t^a\,C_{Dt}^a\,\frac{\sin\epsilon_a}{1\;-\;\frac{\delta_a}{2}\left(1-\frac{C_{Dl}^a\,A_l^a}{C_{Dt}^a A_t^a}\right)\sin^2 2\epsilon_a} \qquad (2)$$

where F_x^a and F_y^a are longitudinal and transverse wind force components, ρ_a is air density, V_a is wind speed, A_l^a and A_t^a are longitudinal and transverse above water areas, C_{Dl}^a and C_{Dt}^a are longitudinal and transverse wind drag coefficients, ϵ_a is wind direction, and δ_a is a wind force deflection parameter based on ship above water geometry. Figure 1 shows the direction conventions for forces and wind direction.

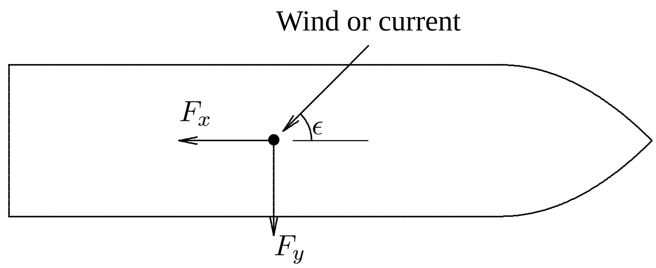

Figure 1: *Axis System for Wind and Current Forces*

3 Current Forces on Ships

For current forces acting on a ship, there is no comprehensive reference available. However, available data in the open literature can be used to estimate the current forces by considering the separate cases of longitudinal and lateral currents.

For lateral currents, the associated forces can be estimating by considering the ship to be a bluff body. For steady current velocity, the ocean surface can be considered as a rigid flow boundary. The force acting on the ship in a transverse current can be approximated by:

$$F_y^w = \frac{1}{2}\,\rho_w\,V_w^2\,A_t^w\,C_{Dt}^w \;\text{ for } \epsilon_w = 90^{\mathrm{o}} \tag{3}$$

where F_y^w is the transverse current force, ρ_w is water density, A_t^w is the transverse underwater area, C_{Dt}^w is the transverse drag coefficient, and ϵ_w is the current direction. The transverse water area A_t^w can be easily determined if the ship draft along the hull length and appendage dimensions are known. The drag coefficient C_{Dt}^w can be estimated by considering the two limiting cases of the ship being represented by a long circular cylinder and a long flat plate. Drag coefficients for circular cylinders are given in sources such as Hoerner [4] and Streeter and Wylie [5]. The drag coefficient of a circular cylinder is dependent on Reynolds number, which is given by the following for a ship representing a half-cylinder:

$$Re_{2T}^w = \frac{V_w\,2T}{\nu_w} \tag{4}$$

where T is ship draft and ν_w is the kinematic viscosity of water. For a representative case of V_w = 2 m/s (4 knots), T = 5 m, and $\nu_w = 10^{-6}$ m^2/s, the Reynolds number will be 2×10^7, leading to a lateral drag coefficient of approximately 0.8 Alternatively, the drag coefficient for a flat plate is discussed by Hoerner. For this case, flow separation and drag can be considered independent of Reynolds number but dependent on aspect ratio given by:

$$a^w \;=\; \frac{2T}{L} \tag{5}$$

The above aspect ratio includes a factor of 2 in the numerator because the ocean surface is considered to be a rigid flow boundary with associated flow symmetry. For a representative case with ship draft T of 5 m and ship length L of 120 m, the associated aspect ratio a_w will be 0.08, leading to a transverse drag coefficient of approximately 1.3. In summary, the transverse drag coefficient C^w_{Dt} for a ship likely falls between the limiting values of 0.8 and 1.3 for a circular cylinder and flat plate.

For longitudinal currents, the associated forces can be estimated using the extensive literature on ship resistance. As given in Newman [6], ship resistance can be expressed as follows:

$$F^w_x \;=\; \frac{1}{2}\,\rho_w\,V_w^2\,S_w\,\left[C^w_F(Re^w_L) \;+\; C^w_R(Fn)\right] \quad \text{for } \epsilon_w = 0^\circ \tag{6}$$

where S_w is hull wetted surface area, C^w_F is the frictional resistance coefficient, Re^w_L is Reynolds number based on hull length, C^w_R is the residual resistance coefficient, and Fn is the Froude number. The Reynolds number and Froude number are evaluated by:

$$Re^w_L \;=\; \frac{V_w\,L}{\nu_w} \tag{7}$$

$$Fn \;=\; \frac{V_w}{\sqrt{g\,L}} \tag{8}$$

where L is ship length between perpendiculars and g is gravitational acceleration. For a representative case with current velocity V_w of 2 m/s, and ship length L of 120 m, the Reynolds number Re^w_L will be 2.4×10^8 and the Froude number Fn will be 0.06. Based on data presented by van Manen and van Oossanen [2], the frictional resistance coefficient will be approximately 0.002 and the residual resistance coefficient will be approximately 0.0005. For a naval ship in currents of 5 knots and less, both frictional and residual resistance coefficients will have little variation with current velocity (i.e., force will be proportional to the square of current velocity).

To model the variation of current forces with angle of attack, the form developed by Blendermann for wind forces appears to be suitable. Assuming residual resistance to be negligible, the current forces acting on the ship for arbitrary angles of attack are:

$$F^w_x \;=\; \frac{1}{2}\,\rho_w\,V_w^2\,S_w\,C^w_{Dl}\,\frac{\cos\epsilon_w}{1 \;-\; \frac{\delta_w}{2}\left(1 - \frac{C^w_{Dl}\,S_w}{C^w_{Dt}\,A^w_t}\right)\sin^2 2\epsilon_w} \tag{9}$$

$$F_y^w \;=\; \frac{1}{2}\,\rho_w\,V_w^2\,A_t^w\,C_{Dt}^w\,\frac{\sin\epsilon_w}{1\;-\;\frac{\delta_w}{2}\left(1-\frac{C_{Dl}^w\,S_w}{C_{Dt}^w\,A_t^w}\right)\sin^2 2\epsilon_w} \tag{10}$$

The main difference between the current force equations above and the wind force equations Equations (1) and (2) is that the longitudinal current force is referenced to the wetted surface area S_w due to the dominant role of skin friction. The longitudinal current force in Equation (9) is expressed in terms of a single drag coefficient given by:

$$C_{Dt}^w \;=\; C_F^w(Re_L^w)\;+\;C_R^w(Fn) \tag{11}$$

4 Induced Drift Velocity

The drift velocity induced by current and winds forces is of interest to ship operators. Drift velocity can be estimated by considering the ship to be drifting along with the current at velocity V_w plus a relative drift velocity V_r induced by the wind. The relative drift velocity can be evaluated by considering equilibrium between air and water drag forces. Assuming the relative drift velocity is small relative to wind velocity, the relative drift velocity for longitudinal winds is:

$$V_r \;=\; V_a\,\sqrt{\frac{\rho_a\;A_l^a\;C_{Dl}^a}{\rho_w\;S_w\;C_{Dl}^w}} \tag{12}$$

Similarly, the relative drift velocity for transverse winds is:

$$V_r \;=\; V_a\,\sqrt{\frac{\rho_a\;A_t^a\;C_{Dt}^a}{\rho_w\;A_t^w\;C_{Dt}^w}} \tag{13}$$

The relative transverse velocity is of greater practical relevance than the relative longitudinal velocity because the ship propeller can easily compensate for longitudinal drift velocity.

5 Predictions of Wind and Current Forces for Canadian Forces Ships

Table 1 gives all parameters required for evaluating wind and current forces acting on HALIFAX, IROQUOIS, and AOR ships. For HALIFAX and IROQUOIS, only a single draft is considered for each ship because the difference between operational light and deep departure drafts are only 0.3 m for HALIFAX and 0.1 m for IROQUOIS. For AOR, both full load and light maneuvering conditions are considered because of their significant differences. The longitudinal and transverse air drag coefficients in Table 1 are based on values published by Blendermann [3]. Deflection parameters for both wind and current forces are assumed to be 0.5 based on values given by Blendermann. Note that wind and current force magnitudes are not very sensitive to the deflection parameters. The longitudinal water drag coefficient value of 0.003 includes contributions from frictional and residual drag. For each CF ship considered in this study, the underwater portion of the hull is more representative of a circular cylinder than a flat plate. The rudder and skeg, which are included in the transverse areas of Table 1, contribute less than 5 percent of the total transverse drag area for each ship. The total transverse drag coefficient of each ship is estimated to be 1.0, with this value likely being conservative.

Computations indicate that the variation of wind drag forces with angle of attack is approximately the same for all ships. Similarly, the variation of current drag forces with angle of attack is approximately the same for all ships. Figures 2 and 3 show the variation of relative longitudinal and transverse wind and current forces acting on HALIFAX with wind and current heading. The negative longitudinal forces in Figure 2 for headings greater than 90 degrees represent the ship being pushed forward by wind or current. For wind and current headings of 45°, the wind and current forces on all 3 DND ships are:

$$F_x^a(45^o) = 0.91\ F_x^a(0^o) \quad (14)$$
$$F_y^a(45^o) = 0.91\ F_y^a(90^o) \quad (15)$$
$$F_x^w(45^o) = 0.94\ F_x^w(0^o) \quad (16)$$
$$F_y^w(45^o) = 0.94\ F_y^w(90^o) \quad (17)$$

Tables 2 to 9 give wind and current forces acting on CF ships. Note that wind and current forces are proportional to the square of velocity. The tables indicate that longitudinal forces are small relative to lateral forces. At a heading of 45 degrees, the longitudinal forces have negligible influence on total absolute force. Figures 4 to 7 show wind and current forces for head and beam directions, and include force scales for units of both kiloNewtons (SI) and tons (British). Note that the longitudinal wind forces for HALIFAX and IROQUOIS are identical in Figure 4

Table 1: *Parameters for Current and Wind Forces for Canadian Navy Ships*

	HALIFAX	IROQUOIS	AOR Full	AOR Light
Draft	5.0 m	5.0 m	10.5 m	7.5 m
Longitudinal wind area A_l^a	210 m^2	210 m^2	380 m^2	448 m^2
Transverse wind area A_t^a	1380 m^2	1190 m^2	1887 m^2	2369 m^2
Wetted surface area S_w	1990 m^2	2020 m^2	5197 m^2	4231 m^2
Transverse current area A_t^w	520 m^2	510 m^2	1526 m^2	1043 m^2
The following properties are assumed to be the same for all ships				
Longitudinal air drag coefficient C_{Dl}^a		0.60		
Transverse air drag coefficient C_{Dt}^a		1.0		
Wind deflection parameter δ_a		0.5		
Air density ρ_a		1.25 kg/m^3		
Longitudinal water drag coefficient C_{Dl}^w		0.003		
Transverse water drag coefficient C_{Dt}^w		1.0		
Water deflection parameter δ_w		0.5		
Water density (salt) ρ_w		1025 kg/m^3		
Water kinematic viscosity ν_w		1×10^{-6} m^2/s		

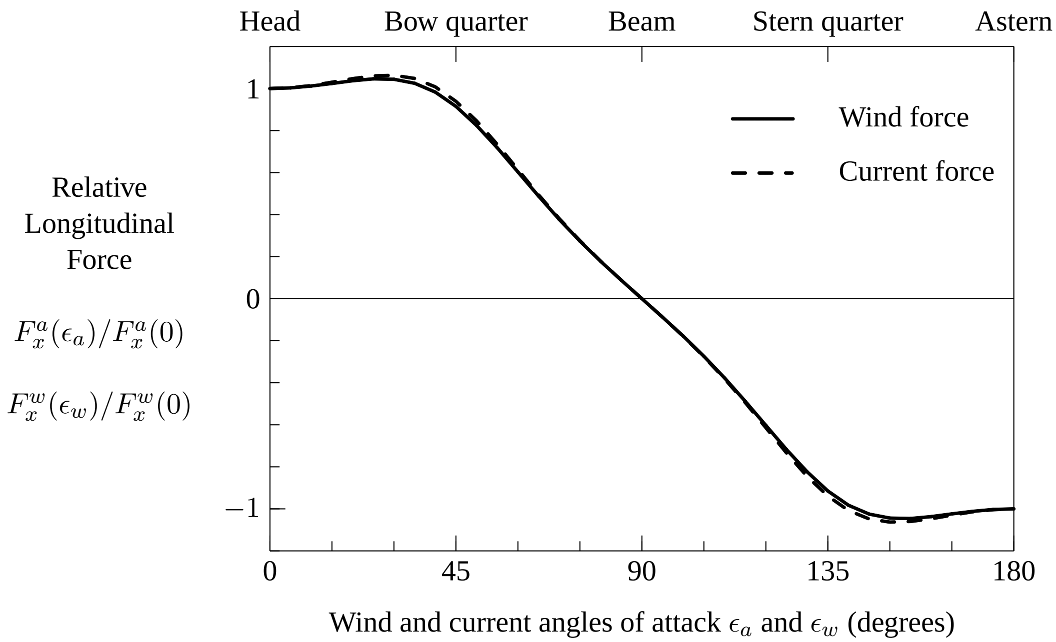

Figure 2: *Relative Longitudinal Wind and Current Forces Versus Heading for HALIFAX*

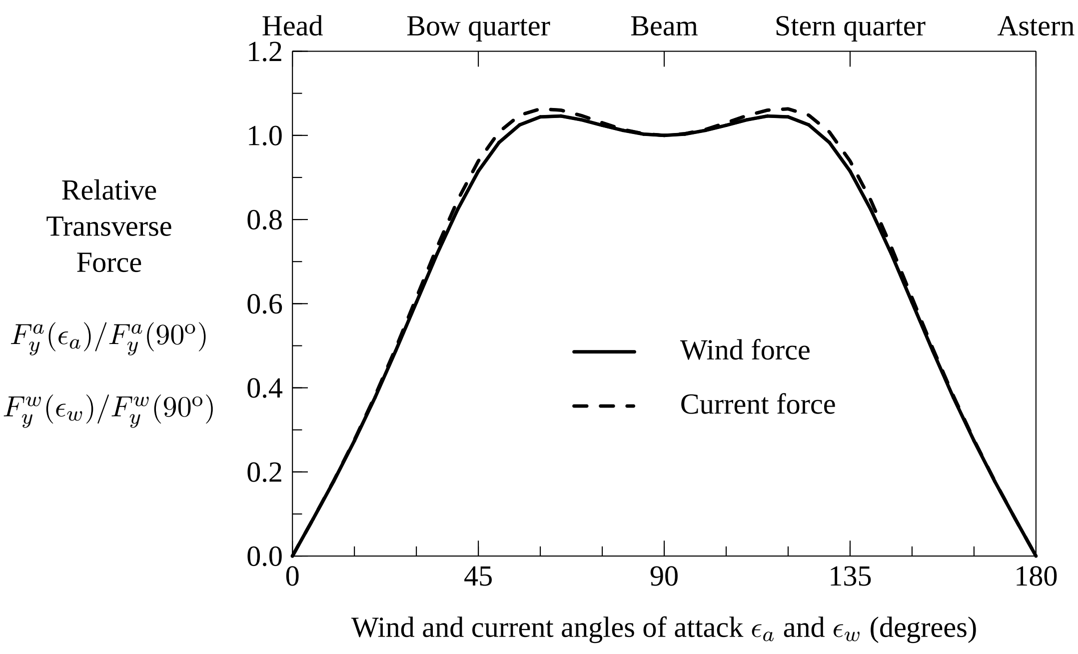

Figure 3: *Relative Transverse Wind and Current Forces Versus Heading for HALIFAX*

Table 2: *Wind Forces on HALIFAX*

Wind speed V_a	Wind Force (kN)		
(knots)	Head wind	Quartering wind	Beam wind
5	1	5	6
10	2	21	23
15	5	47	51
20	8	84	92
25	13	131	143
30	19	188	206
35	26	256	280
40	33	334	366
45	42	423	463
50	52	523	572

Table 3: *Current Forces on HALIFAX*

Current speed V_a	Current Force (kN)		
(knots)	Head current	Quartering current	Beam current
1	1	67	74
2	3	269	295
3	7	605	664
4	13	1075	1181
5	20	1679	1845

Table 4: ***Wind Forces on IROQUOIS***

Wind speed V_a		Wind Force (kN)	
(knots)	Head wind	Quartering wind	Beam wind
5	1	5	5
10	2	18	20
15	5	41	44
20	8	72	79
25	13	113	123
30	19	162	178
35	26	221	242
40	33	289	316
45	42	366	399
50	52	451	493

Table 5: *Current Forces on IROQUOIS*

Current speed V_a		Current Force (kN)	
(knots)	Head current	Quartering current	Beam current
1	1	65	72
2	3	262	288
3	7	589	647
4	13	1047	1150
5	21	1636	1798

Table 6: *Wind Forces on AOR, Full Load Condition*

Wind speed V_a	Wind Force (kN)		
(knots)	Head wind	Quartering wind	Beam wind
5	1	7	8
10	4	29	31
15	9	65	70
20	15	115	125
25	24	179	195
30	34	258	282
35	46	351	383
40	60	459	500
45	77	581	633
50	94	717	782

Table 7: *Current Forces on AOR, Full Load Condition*

Current speed V_a	Current Force (kN)		
(knots)	Head current	Quartering current	Beam current
1	2	189	208
2	8	756	830
3	19	1700	1868
4	34	3022	3321
5	53	4722	5189

Table 8: *Wind Forces on AOR, Light Maneuvering Condition*

Wind speed V_a		Wind Force (kN)	
(knots)	Head wind	Quartering wind	Beam wind
5	1	9	10
10	4	36	39
15	10	81	88
20	18	144	157
25	28	225	245
30	40	324	353
35	55	441	481
40	71	575	628
45	90	728	795
50	111	899	982

Table 9: *Current Forces on AOR, Light Maneuvering Condition*

Current speed V_a		Current Force (kN)	
(knots)	Head current	Quartering current	Beam current
1	2	129	142
2	7	516	567
3	16	1161	1276
4	28	2064	2268
5	43	3226	3544

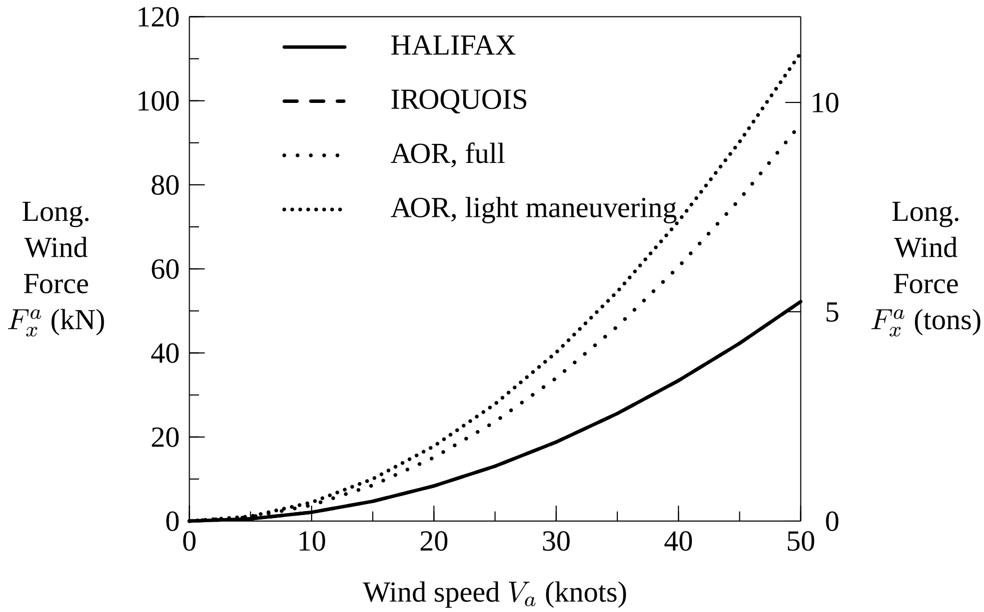

Figure 4: *Longitudinal Wind Force Versus Wind Velocity in Head Wind*

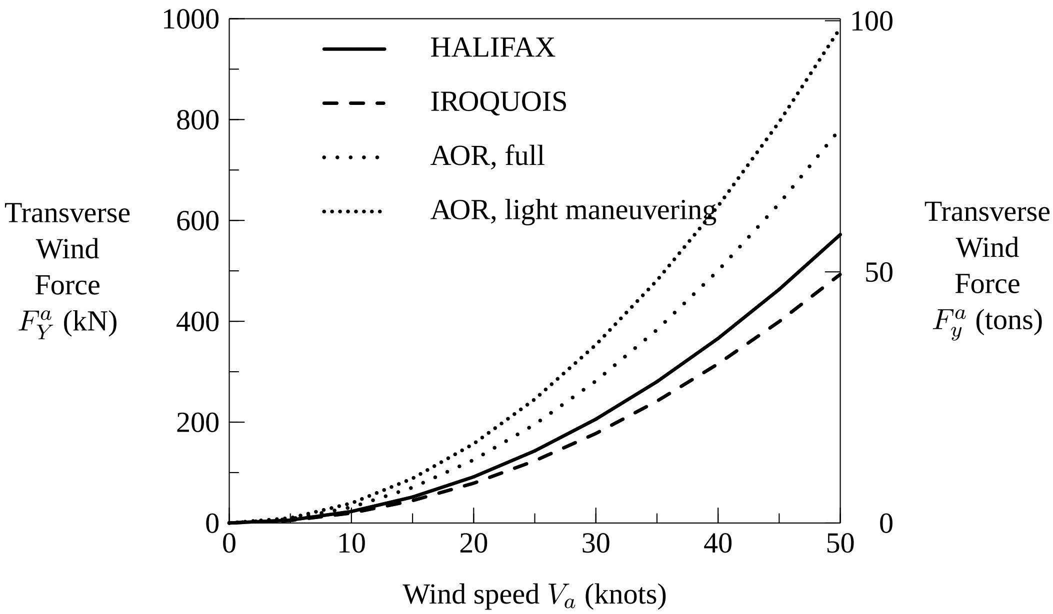

Figure 5: *Transverse Wind Force Versus Wind Velocity in Beam Wind*

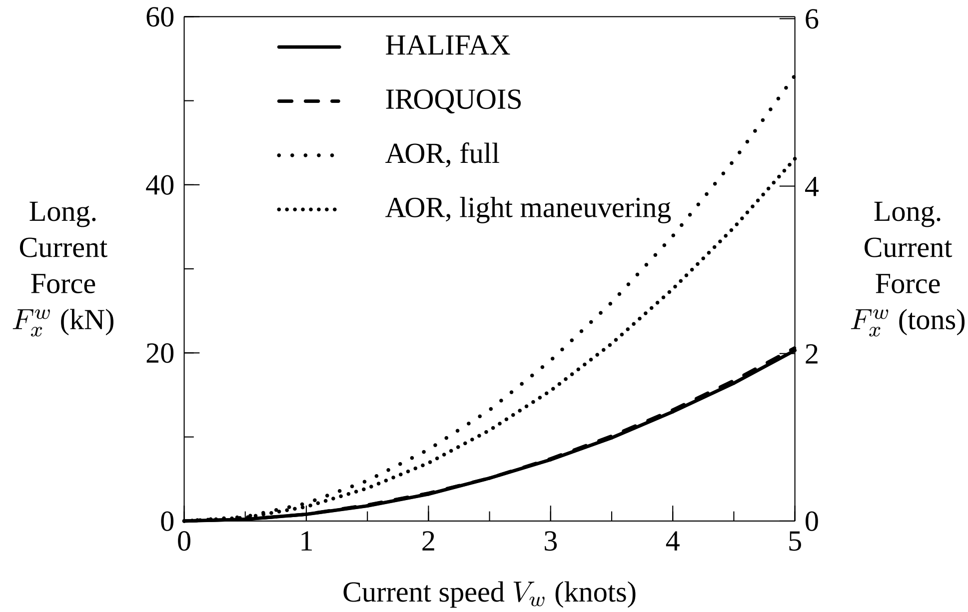

Figure 6: *Longitudinal Current Force Versus Current Velocity in Head Wind*

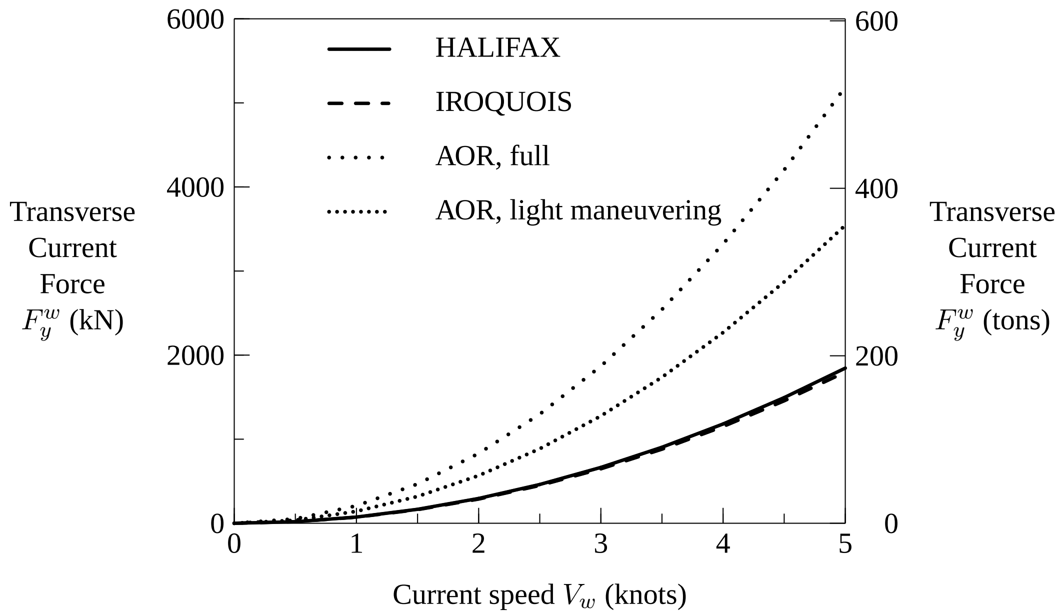

Figure 7: *Transverse Current Force Versus Current Velocity in Beam Wind*

Table 10 gives wind-induced transverse drift velocities in beam winds. As expected, the AOR has a higher wind-induced drift velocity for the light maneuvering condition than for the full load condition. The relative drift velocities in Table 10 are less than a nominal value of 10 percent often assumed for Canadian naval ships. A possible explanation for this discrepancy is that the nominal value of 10 percent includes the effect of wind-induced currents, which can be approximately 3 percent of wind speed.

Table 10: *Transverse Relative Drift Velocity as Percentage of Wind Speed for Canadian Navy Ships*

HALIFAX	5.6%
IROQUOIS	5.2%
AOR full load	3.9%
AOR light maneuvering	5.3%

6 Uncertainties in Predicted Forces

When applying the present force predictions, it is important to be aware of the associated level of uncertainties in predictions. In the present work, there are uncertainties regarding the drag coefficients selected for given ship geometries. Data from Blendermann [3] suggest that longitudinal drag coefficients will have a standard error of approximately 20 percent, while transverse drag coefficients will have a standard error of approximately 10 percent. To account for these uncertainties, the drag coefficients chosen for the present computations (see Table 1) are slightly conservative.

In an operational context, the largest uncertainties will likely be associated with estimates of wind and current velocities. Wind and current forces are both proportional to velocity squared; thus, a relative error in wind or current velocity will lead to a relative error in drag force which is approximately twice as large. Consequently, it is likely that errors due to wind or current velocities will lead to errors larger than those due to drag coefficients.

Wind and current forces will also vary with ship loading condition. This effect will likely be minor for HALIFAX and IROQUOIS, which maintain relatively constant drafts. For AOR, large changes in drafts will significantly affect wind and current profile, but will have little effect on wetted surface area. Changes to profile areas can be evaluated by:

$$A_l^a(T + \Delta T) = A_l^a(T) - B\,\Delta T \tag{18}$$

$$A_t^a(T + \Delta T) = A_t^a(T) - L\,\Delta T \tag{19}$$

$$A_t^w(T + \Delta T) = A_t^w(T) + L\,\Delta T \tag{20}$$

where ΔT is change in draft and B is ship beam.

7 Conclusions

Predictions have been developed for wind and current forces acting on Canadian Forces ships during tug operations. Transverse forces in transverse flows are much larger than longitudinal forces in longitudinal flows. For wind and currents approaching from 45 degrees off the bow, transverse forces are much larger than longitudinal forces.

Tables have been developed for wind and current forces on HALIFAX, IROQUOIS and AOR ships. In an operational context, the greatest errors in force predictions will likely be due to errors in wind or current velocities.

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Symbols

A_l^a, A_t^a	longitudinal and transverse wind profile areas
a^w	aspect ratio of underwater portion of ship
B	ship beam
C_{Dl}^a, C_{Dt}^a	longitudinal and transverse air drag coefficients
C_{Dl}^w, C_{Dt}^w	longitudinal and transverse water drag coefficients
C_F^w	longitudinal water friction drag coefficient
C_R^w	longitudinal water residual drag coefficient
F_x^a, F_y^a	longitudinal and transverse wind forces
F_x^w, F_y^w	longitudinal and transverse wind forces
Fn	Froude number
g	gravitational acceleration
Re_L^w	ship Reynolds number in water based on ship length
Re_{2T}^w	ship Reynolds number in water based on twice ship draft
S_w	wetted surface area
T	ship draft
V_a	air velocity
V_r	wind-induced ship velocity relative to currents
V_w	water velocity
ΔT	change in ship draft
δ_a	wind force deflection parameter
δ_w	current force deflection parameter
ϵ_a	wind relative direction
ϵ_w	current relative direction
ν_w	kinematic viscosity of water
ρ_a	air density
ρ_w	water density

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This report presents predictions of wind and current forces on Canadian Forces ships during towing operations. Longitudinal and transverse forces are treated as functions of incident flow direction. For the ship geometries considered, transverse forces arising from transverse flows are much greater than longitudinal forces from longitudinal flow. For winds or currents from the bow quarter (45 degrees), transverse forces are much greater than longitudinal forces. The report includes tables of wind and current forces acting on HALIFAX, IROQUOIS and AOR ships. In an operational context, the greatest errors in force predictions will likely be due to errors in wind or current velocities.

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